Task Engagement and Attentional Resources: Multivariate Models for Individual Differences and Stress Factors in Vigilance

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Running head: Task engagement and vigilance

Manuscript type: Extended Multi-Phase Study

Word Count: Reference Word Count:

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ABSTRACT

Objective: Two studies tested multivariate models of relationships between subjective task engagement and vigilance. The second study included a stress factor (cold infection). Modeling tested relationships between latent factors for task engagement and vigilance, and the role of engagement in mediating effects of cold infection.

Background: Raja Parasuraman's research on vigilance identified several key issues including the roles of task factors, arousal processes and individual differences, within the framework of resource theory. Task engagement is positively correlated with performance on various attentional tasks, and may serve as a marker for resource availability.

Method: In Study 1, 229 participants performed simultaneous and successive vigilance tasks. In Study 2, 204 participants performed a vigilance task and a variable foreperiod simple reaction time task on two separate days. On day two, 96 participants performed while infected with a naturally-occurring common cold. Task engagement was assessed in both studies.

Results: In both studies, vigilance decrement in hit rate was observed, and task performance led to loss of task engagement. Cold infection also depressed both vigilance and engagement. Fitting sructural equation models (SEMs) indicated that simultaneous and successive tasks should be represented by separate latent factors (Study 1), and task engagement fully mediated the impact of cold infection on vigilance but not reaction time (Study 2).

Conclusions: Modeling individual differences in task engagement elucidates the role of resources in vigilance and underscores the relevance of Parasuraman's vision of the field.

Application: Assessment of task engagement may support diagnostic monitoring of operators performing tasks requiring vigilance.

Keywords

Vigilance, fatigue, task engagement, cold infection, diagnostic monitoring

Précis

Structural equation modeling was used to test relationships between vigilance and task engagement in two studies. Task engagement had a direct influence on simultaneous but not successive vigilance (Study 1). Task engagement fully mediated the impact of cold infection on vigilance, but not on variable foreperiod reaction time (Study 2).

INTRODUCTION

Raja Parasuraman made essential contributions to both the theory and the application of vigilance research. His early work with Roy Davies (Davies & Parasuraman, 1982) laid the foundations for the attentional resource theory of vigilance that was subsequently elaborated by Warm, Dember and Hancock (1996). Parasuraman (1987) was also one of the first to discern that widespread introduction of automation would lend new impetus to vigilance as a practical human factors issue. He introduced the field of neuroergonomics (Parasuraman, 2003), which integrates experimental and psychophysiological methods and lends itself to multiple domains of human factors. These include countering loss of vigilance by using psychophysiological markers for vigilance to drive adaptive automation (Byrne & Parasuraman, 1996).

The present article reports multivariate analyses of data from two studies of vigilance that build on several theoretical advancements made by Parasuraman and his colleagues:

- *Simultaneous vs. successive task types*. Davies and Parasuraman (1982) noted that vigilance tasks could be divided into those requiring a comparative judgment (simultaneous discrimination) and those requiring an absolute judgment (successive discrimination). The latter require holding information in short term memory (STM), and so are more cognitively demanding than simultaneous tasks. Indeed, Parasuraman (1979) showed that tasks characterized by both high event rate and a successive discrimination were especially apt to show perceptual sensitivity decrement over time. Subsequently, a meta-analysis of factors influencing sensitivity decrement (See, Howe, Warm, & Dember, 1995) confirmed that high event rate successive tasks are prone to large magnitude performance decrement. See et al. (1995) also found that sensitivity decrement was more prevalent than Davies and Parasuraman (1982) stated, and additional factors such as whether the task was sensory or cognitive in nature also played important roles in controlling the magnitude of the decrement.

- *The role of arousal.* A connection between loss of arousal and loss of sustained attention has been known since Mackworth's (1950) finding that amphetamine mitigates vigilance decrement, but the causal role of arousal has been harder to establish. Davies and Parasuraman (1982) pointed out that several classical arousal indices such as heart rate and skin conductance are not reliably correlated with vigilance, although they concluded that electroencephalographic (EEG) measures were more promising, as were indices of mental effort. Subsequent work confirmed the necessity of distinguishing between different "arousal" indices (Panicker & Parasuraman, 1998). Indices that may be more closely tied to resource utilization include hemodynamic indices of frontal brain metabolism (Warm, Matthews & Parasuraman, 2009). The importance of differentiating different brain systems has also become apparent (Langner & Eickhoff, 2013).
- *The elusiveness of individual differences*. Anyone familiar with vigilance data knows that participants differ considerably in both overall performance and susceptibility to vigilance decrement. Davies and Parasuraman (1982) reviewed the literature and concluded that "..the practical implications of research with individual differences in vigilance are disappointing" (p. 140). More recently, Finomore, Matthews and Warm (2008) reached similar conclusions, although the role of general cognitive ability seems stronger than was apparent at the time of the 1982 book. Building on Parasuraman's (e.g., 1976) empirical studies, Davies & Parasuraman (1982) suggested that identifying consistent individual differences depends on controlling task factors such as stimulus modality and the type of target discrimination required

In addition to advancing the theory of vigilance, Parasuraman also contributed to a key methodological development, the design of relatively short duration tasks for investigating vigilance decrement. Nuechterlein, Parasuraman and Jiang (1983) modified the Continuous Performance Test, which requires detection of a single target digit. They showed that when the visual stimuli were blurred, substantial perceptual sensitivity decrement was found over intervals as short as 5-10 min. Pattern-masking the stimulus is equally effective in producing rapid decrement (Matthews, Davies & Lees, 1990; Temple et al., 2000). The resource theory explanation (Parasuraman, Warm & Dember, 1987; Warm, Parasuraman & Matthews, 2008) is that the high cognitive demands of processing degraded stimuli lead to rapid resource depletion. Reduced resource availability is expressed as loss of sensitivity, provided that the task is sufficiently resource-demanding. Short-duration tasks show many of the key characteristics of longer-duration tasks (Shaw et al., 2010). That is, they show similar effects on performance of various psychophysical parameters, task demand manipulations, and stressors. Short-duration tasks also provoke similar subjective and psychophysiological responses to longer tasks. Methodologically, the use of short-duration tasks makes it much easier than previously to explore the correlations of vigilance with other cognitive tasks (e.g., Matthews, Davies & Holley, 1993).

We can further investigate the roles of task type, arousal and individual difference factors by assessing subjective task engagement. Matthews et al. (2002) proposed a three-dimensional model of stress states related to task performance which defines broad factors of task engagement, distress, and worry. Task engagement brings together energetic arousal, task motivation, and concentration; lack of task engagement corresponds to a fatigue state of tiredness, apathy, and distractibility (see Matthews et al., 2013, for a review). Initial studies of self-report arousal and vigilance suggested that subjective energetic arousal might index attentional resource availability. A series of studies (reviewed by Matthews & Davies, 1998) showed that pre-task energetic arousal only reliably predicts perceptual sensitivity if the task shows a vigilance decrement, and therefore is likely to be resource- rather than data-limited (Norman & Bobrow, 1975; Parasuraman et al., 1987). Furthermore, a variety of qualitatively different demand manipulations, including stimulus degradation, task pacing, and multi-tasking, were sufficient to produce sensitivity to individual differences in energetic arousal, consistent with the resource model. Later studies (e.g., Matthews et al., 2010a) showed that the broader-based factor of task engagement was equally predictive of vigilance, and it also correlated with cerebral bloodflow velocity (CBFV) in the middle cerebral arteries, which is a psychophysiological resource index (Warm et al., 2009).

This article reports multivariate modeling of data from two studies of visual vigilance that have been briefly reported before (Matthews et al., 1999, 2001) to further test the validity of task engagement as a marker for resource availability. We focused on individual differences in overall (mean) detection rate but not in vigilance decrement. Engagement typically has similar relationships with the two types of performance measure, although findings vary somewhat across studies. Matthews et al. (2014) found that task engagement correlated positively with both overall detections, and an index of temporal decrement, but correlation magnitudes were larger for overall vigilance By contrast, two further studies (Matthews et al., 2010a; Shaw et al., 2010) found that engagement predicted a smaller-magnitude vigilance decrement with initial level of vigilance controlled. Thus, in some instances, the resource-dependence of performance may increase over time, but for present purposes, it was considered that overall performance provided an acceptable vigilance metric.

Study 1 tested the degree of overlap between the resources required for simultaneous and successive tasks, given that tasks of these types may differ qualitatively as well as in level of cognitive demand. Study 2 investigated whether loss of task engagement may mediate the impact of an external stressor – common cold infection – on vigilance, or whether changes in engagement are incidental to performance change, a finding that would challenge the resource model. In both studies, data were analyzed using structural equation modeling (SEM: Bentler, 2008). The advantages of SEM here are two-fold. First, SEMs distinguish the *structural model* of relationships between latent constructs from the *measurement model* that defines latent constructs in terms of measured variables, allowing greater precision in modeling relationships between constructs such as vigilance and task engagement. Second, SEMs include causal paths so that theory-driven hypotheses such as mediating role for task engagement in stressor effects may be tested directly.

STUDY 1

Typically, the resource theory of vigilance has assumed that signal detection is controlled by a unitary resource that can be allocated to a variety of different tasks (Parasuraman et al., 1987; Warm & Dember, 1998). Vigilance decrement depends primarily on the overall difficulty of the task, rather than any specific cognitive demand factor (See et al., 1995), which supports the assumption. Indeed, while the original work of Davies and Parasuraman (1982) emphasized a memory load as a necessary condition for perceptual sensitivity decrement, demanding simultaneous tasks imposing minimal memory load also show significant decrement (Matthews, Davies & Lees, 1990; Parasuraman & Mouloua, 1987; See et al., 1995). A case can also be made that multiple resources may contribute to vigilance, consistent with general attentional theory (Boles, Bursk, Phillips, & Perdelwitz, 2007; Wickens, 2008). More specifically, if successive, but not simultaneous, vigilance tasks require STM or working memory (WM), then these tasks may draw on an additional type of resource not required for simultaneous discriminations. For example, Humphreys and Revelle (1984) distinguished a resource for sustained throughput of information (attention) from a second resource for STM.

The role of memory in vigilance decrement may be seen from two perspectives. One is to equate memory demands with general executive functioning, as in Baddeley's (2012) working memory model. If deteriorating executive control of attention is a key factor in vigilance decrement (Thomson, Besner & Smilek, 2015), then increasing memory load may be one of several means for increasing demands for executive control. A second perspective is to examine memory processes that may be vulnerable to temporal decrement in finer detail. Caggiano and Parasuraman (2004) suggested that spatial working memory representations may be especially sensitive to depletion over time, on the basis of a dual-task study. Helton and Russell (2011, 2013) conducted two further studies comparing the impacts of spatial and verbal memory loads, which correspond to different short-term stores in the Baddeley (2012) model. Consistent with Caggiano and Parasuraman's (2004) finding, they found that visuospatial vigilance is especially prone to vigilance decrement. However, they also note the importance of controlling for task demands, and the availability of different strategies for processing verbal information. In addition, dual-task interference in vigilance performance associated with both visuospatial and verbal demands suggests a domain-general influence on vigilance (i.e., resources or executive control), as well as domain-specific influences.

Evidence from studies of individual differences is mixed. Parasuraman and Davies (1977) showed that task pairs matched for discrimination type (i.e., simultaneous or successive) were more highly correlated than unmatched pairs, implying the two types of task might draw on different resource pools. By contrast, Matthews et al. (1993) used various short vigilance tasks designed to be cognitively demanding, and found that simultaneous and successive tasks were generally significantly correlated, consistent with there being a resource common to both task types. Perceptual sensitivity on both simultaneous and successive tasks was correlated with performance on a resource-limited visual search task, although correlation magnitudes tended to be higher for successive tasks. These findings suggested that successive tasks might simply be more resource-demanding than simultaneous ones. Matthews et al. (2014) used SEM to show that task engagement influenced simultaneous and successive vigilance tasks to a similar extent, consistent with engagement indexing a common resource.

In Study 1, participants performed both simultaneous and successive 12 min vigilance tasks, similar to those employed by Matthews et al. (1993). The participant viewed pairs of horizontal lines whose length varied randomly and rapidly around a mean value. The target was a longer line; the flickering appearance of the lines made it difficult to discriminate targets from non-targets. On the simultaneous task only one of the two lines was longer, so detection required comparison of the two lines, with no memory load. On the successive task, both lines were longer, requiring a comparison with the representation in memory of the previous line pair, increasing the demands of the task. Matthews et al. (1993; Experiment 3) found that both versions of the task showed significant perceptual sensitivity and hit rate decrements over time.

Subjective task engagement was measured before and after task performance. We applied SEM to address two issues. First, we tested whether better fit to the data was obtained by modeling a single latent vigilance factor that influenced all measures of vigilance taken, or by two correlated factors that separated simultaneous from successive vigilance. A simple unitary model of vigilance predicts that modeling two factors would not improve model fit relative to the single-factor model. In fact, we found that the two-factor model afforded superior fit. Second, assuming a two-factor model, we tested whether task engagement influenced both simultaneous and successive vigilance independently, or whether engagement influenced one factor only. If task engagement is a marker for a general resource for visual attention (Matthews et al., 2010b), then it might be expected to influence both factors.

Method

This study was briefly reported by Matthews et al. (1999). In this article, we report only those features of the method relevant to the goal of multivariate modeling of task engagement and vigilance. The study included manipulations intended to test the effects of drinking tea on vigilance. Caffeine dosage and the participant's expectancy of ingesting caffeine were manipulated independently. Participants included 199 individuals who were run using a 3 × 2 (caffeine: 0, 50 or 100 mg × expectancy: caffeinated or decaffeinated) between subjects-design. An additional 30 participants drank hot water only. Study manipulations had no effect on task engagement, and no main effects on vigilance hit rate or decrement. Thus, modeling was performed on the complete, pooled data set.

Participants. 229 students aged between 17 and 30 (113 men and 116 women) were recruited at the University of Dundee, Scotland, and paid for their participation. Exclusion criteria included medical issues, smoking, and taking prescribed or non - prescribed psychoactive drugs. Participants were instructed to refrain from caffeine and alcohol for 12 hours prior to the study, and food for 2 hours.

Tasks and measures. All participants performed simultaneous and successive line length discrimination tasks similar to those of Matthews et al. (1993). The participant viewed pairs of horizontal lines presented on a computer screen for 300 ms at a rate of 60/minute. The target (probability 0.25) was a longer line stimulus. Base line length was 36 mm. During stimulus presentation, length of each line varied randomly around this base length (see Matthews et al., 1993). Target lines were 20% longer. From the participant's perspective, the left end of the lines is fixed in location, but the position of the right end varies frequently, producing a flickering impression. This variation in length made it difficult to discriminate the longer lines from those of standard length.

On the simultaneous task (SIM) targets included a single longer line, presented in the upper or lower position at random, whereas successive task (SUC) targets were two longer lines (see Figure 1). Each task was of 12 minutes duration, analyzed as four three-minute periods.

The Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999, 2002, 2013) was administered before and after performance of the vigilance tasks. The DSSQ assesses 10 first-order dimensions of subjective state, using 6-8 item scales. Second-order factors of task engagement, distress and worry are estimated as a weighted sum of the 10 first-order scales using regression weights taken from a large normative sample (Matthews et al., 1999). In this article, the second-order factor scores were used only in initial analyses that tested for the impact of task factors on task engagement, and for bivariate associations between engagement and vigilance. First-order factors associated with engagement were used for multivariate modeling.

Procedure. Following administration of the pre-task DSSQ, participants performed both vigilance tasks, with a short break between them. Order of administration was counterbalanced across the sample. Following performance of the two tasks, they completed a post-task DSSQ.

Results

Initial analyses. We report analyses that tested three key assumptions of the resource model: (1) vigilance tasks show performance decrements over time, (2) performing vigilance tasks lowers subjective engagement, and (3) task engagement correlates positively with vigilance. We tested associations of both pre- and post-task engagement with vigilance performance initially; subsequent multivariate analyses focused on the post-task measure. Nine participants failed to complete the study, and so analyses are based on an *N* of 220.

We used hit rate (% targets detected) to index performance on the vigilance tasks because false positive rates were too low (<5% for each measure) to support signal detection theory analyses. Task factor effects were analyzed using a 2 × 4 (task type: SIM vs. SUC × task period: 1-4) repeated-measures ANOVA. Box's correction to degrees of freedom was applied where appropriate because of violations of the sphericity assumption. There were significant main effects of task type, $F(1,219) = 152.57$, $p<.01$, $\eta^2_p = .411$, and task period, $F(2.26,439.81) = 63.55$, $p<.01$, $\eta^2_p = .225$. The interaction was not significant. Figure 2 shows that, as expected, the SUC task was harder, and that hit rate declined over time.

Figure 2 about here

Task performance elicited changes in subjective state consistent with expectation. Comparisons of pre- and post-task state showed that task engagement declined ($t(219)=17.42$, $p<.01$, $d=-1.08$), distress increased ($t(219)=9.08$, $p<.01$, $d=.56$) and worry declined non-significantly ($t(219)=1.94$, $p>.05$, $d=-.10$). Mean hit rate, averaged across the four periods, was correlated with pre- and post-task engagement. For the SIM task, the pre- and post-task correlations were .22 and .19; for the SUC task, the corresponding correlations were .22 and .22 (all significant at $p<.01$). The SIM – SUC average hit rate correlation was (.59 $p<.01$).

Multivariate modeling. Alternate models of the data were tested by using maximum likelihood methods to fit SEMs with the EQS package (Bentler, 2008). Measured variables included the three DSSQ scales that primarily contribute to task engagement – post-task energetic arousal, task motivation, and concentration. We used post-task measures as those are most representative of the participant's feeling state during performance. For vigilance, the measured variables were the eight hit rate scores obtained from the two tasks at each 3-min period. Because of violations of the multivariate kurtosis assumption, in addition to overall χ^2, we report robust statistics for goodness of fit (Yuan & Bentler, 2007), including the Satorra-Bentler scaled χ^2, as well as the comparative fit index (CFI) and Root Mean-Square Error of Approximation (RMSEA). The χ^2 test tends to be overly sensitive to small deviations from fit, so the latter two indices were the primary means for determining fit. There are no fixed criteria for acceptable fit, but researchers typically seek CFI $\geq .95$, and RMSEA $\leq .06$ (Weston & Gore, 2006).

Table 1 gives fit indices for four models. Model 1 included two latent factors, a task engagement factor, and a general vigilance factor defined by all eight hit rate measures. It fitted data poorly, and so subsequent modeling included separate SIM and SUC factors (Model 2). We included a path from SIM to SUC, assuming that SUC reflects both the general visual attention resource required for SIM, plus additional processes or resources associated with visual STM. Model 2 included paths from engagement to both vigilance factors. Fit indices were much improved. We then tested whether a more parsimonious model of the impact of engagement on vigilance could be achieved by dropping one or other of the engagement – vigilance paths. A single path model is compatible with engagement indexing a unitary resource for visual attention. Only the engagement – SIM path was significant in Model 2, suggesting that the SUC path might be eliminated. Model 3 included only a path from engagement to the SIM factor, and Model 4 only a path from engagement to the SUC factor. Comparison of these models tested the optimal means for modeling the influence of task engagement on vigilance. Model 3 showed minimal loss of fit. For nested models, change in fit can be tested as the change in χ^2. For Model 3 vs Model 2, $\Delta\chi^2$ (1) = 1.94, NS. For Model 4 vs Model 2, $\Delta\chi^2$ (1) = 14.97, $p<.01$. Thus, Model 3 is preferred on the basis of parsimony and fit. Even the better fitting models showed imperfect fit, especially in relation to the RMSEA index. Because the focus was on comparing the fits of theory-driven models, we did not attempt to improve fit on a post hoc basis. However, inspection of parameter residuals suggested that the models may not capture some of the inter-relationships between specific pairs of vigilance variables.

Table 1 about here

Figure 3 shows Model 3: all paths were significant at $p<.05$ on Bentler's (2008) test. The three latent factors were well-defined by the measured variables. The task engagement factor influenced the SIM factor, which in turn influenced the SUC factor.

Figure 3 about here

Discussion

The SEMs provided straightforward answers to the two issues of interest. First, although performance on the two task versions was quite substantially correlated, consistent with earlier findings on the line length task (Matthews et al., 1993), fit was much better for the two-factor than for the one-factor model. Simultaneous and successive tasks reflect distinct latent constructs, consistent with vigilance theory (Parasuraman & Mouloua, 1987; Warm & Dember, 1998). Both tasks showed substantial temporal decrements in hit rate, implying that both were resource-limited.

Two possible explanations for the two-factor model might be advanced. In modeling relationships between cognitive ability and attention, Schweizer (2010) proposed a hierarchical factor mode, which, at the lower level, discriminates resources necessary for demanding signal detection and discrimination tasks (perceptual control) from resources needed for WM and higher-level cognition (executive control). At a higher level, both resources support a general factor, and Schweizer (2010) viewed both as contributing to sustained attention. Similarly, experimental studies suggest a distinction between perceptual and cognitive load (Lavie, 2006).The demands of the simultaneous task are primarily perceptual, coupled with high time pressure, and so performance might reflect the Schweizer perceptual control factor. To the extent that the successive task requires WM, it may be identified with the executive control factor. With further markers for each factor we might be able to explain the covariance of the simultaneous and successive factors by including a higher-order general factor.

However, there are reasons for doubting this account. The memory component of the successive task corresponds more to STM than to WM. The participant needs to maintain a representation of the standard line length in memory, but no additional processing is necessary. By contrast, WM entails active transformations of information, under executive control. Indeed, Matthews et al. (1993) failed to find any significant associations between successive vigilance and a verbal WM task. An alternative explanation is then that the successive task draws on the same resource as the simultaneous task, but performance additionally requires visual STM, given the additional memory load of the successive version. Previous work (Caggiano & Parasuraman, 2004; Helton & Russell, 2013) suggests that additional demands on visual STM might enhance vigilance decrement, but temporal declines in the two task versions were parallel in the present study.

The second issue of interest was the mechanism for task engagement effects on vigilance. Task engagement correlated with roughly equal magnitude with simultaneous and successive performance. However, modeling suggested that engagement was directly related to simultaneous performance, and indirectly to successive performance. This finding also argues against equating the two factors with perceptual and cognitive resources (Schweizer, 2010). Task engagement was positively associated with perceptual sensitivity on a sustained letter coding task that imposed a high WM load, but which was not perceptually demanding (Matthews et al., 2010a). Using Posner's Attention Network Task (ANT: Fan et al., 2002), Matthews and Zeidner (2012) found that task engagement was positively correlated with executive control of attention. Thus, engagement should be associated with a cognitive control factor, but there was no direct link here. By contrast, the data are compatible with the alternative explanation for the two-factor model. That is, task engagement influences the purer measure of attentional resources afforded by the simultaneous task. This resource might also be identified with the sustained information transfer resource in the Humphreys and Revelle (1984) model. However, there is no known link between engagement and visual STM, and so there is no reason for engagement to have any additional influence on successive vigilance, beyond the resource-dependence common to both task types.

STUDY 2

The first study suggested that task engagement is associated with higher availability of a resource common to both simultaneous and successive vigilance tasks. The second study aimed to address a further key issue in vigilance addressed in Parasuraman's research: the roles of arousal and resource availability in mediating stressor effects (Davies & Parasuraman, 1982; Warm et al., 2008). Specifically, Study 2 tested whether task engagement, as a marker for a unitary visual resource, might mediate the impact of a stressor (cold infection) on vigilance. This study used a different short vigilance task developed by Temple et al. (2000). It requires the participant to discriminate between confusable target and nontarget characters presented briefly against a masking stimuli. Temple et al. (2000) showed that hit rate declines significantly over 12 minutes. Performance correlates with higher task engagement (Matthews et al., 2014; Shaw et al., 2010). Using this task, Helton, Matthews and Warm (2008) used SEM to test a mediation model for effects of airplane jet engine noise on vigilance. A beneficial effect of noise on vigilance was fully mediated by task engagement; jet engine noise tended to elevate task engagement, which in turn benefited vigilance. However, it is unknown whether a similar mediation mechanism can be established for other stressors.

The common cold is caused by viral infections that provoke acute illness of the upper respiratory tract. Cold infections are significant for human factors because they can reduce work productivity (Nichol, Heilly & Ehlinger, 2005), and impair alertness and performance on tasks such as vehicle driving (Smith & Jamson, 2012). Controlled laboratory studies of experimentally-induced and naturally occurring colds show that infection impairs performance on a range of information-processing tasks; effects on alertness and psychomotor speed appear to be more reliable than those on memory (see Smith, 2013, for a review). The role of subjective state change in performance effects is unclear. Colds typically impair mood and subjective alertness (Smith et al., 1992, 1999), but Smith (2012) reported that cold effects on objective cognitive performance were not attributable to mood changes. However, the DSSQ may provide more refined assessment of subjective states than mood ratings do by incorporating motivational and cognitive responses. Given that cold infection produces performance impairments resembling those seen in other low alertness states such as sleep deprivation (Smith, 2012), further investigation of the role of subjective states is warranted. The applied issue is whether loss of task engagement is usefully diagnostic of attentional impairment in cold-infected operators.

In Study 2, a longitudinal design was employed. Participants completed a battery of cognitive tasks, including the Temple et al. (2000) vigilance task, in a healthy state. They were retested subsequently on a second day at which some remained healthy, and others reported cold symptoms. Task engagement was measured on both days. We could thus use SEM to test the stability of the engagement – vigilance association across successive days, and to test whether task engagement mediated the expected impact of infection on vigilance on the second day. A secondary aim of the study was to model influences on another task requiring sustained alertness, variable foreperiod simple reaction time (SRT). A version of this task, the psychomotor vigilance task (PVT), has been widely used in sleep loss research (e.g., Basner & Dinges, 2011), but it is unclear whether PVT performance is controlled by the same factors as conventional vigilance is. Furthermore, the PVT assesses vigilance using reaction time, but accuracy and reaction time appear to index somewhat different sustained attention processes (Funke et al., 2011).

Method

Participants. A total of 204 volunteers were recruited at two sites, and were paid for participation. The first site was a clinical trials facility in Cincinnati, Ohio, at which 92 women and 10 men drawn from the general population (mean age: 39) were recruited. The second site was Cardiff University, Wales, at which 70 female and 32 male college students (mean age: 21) were recruited.

Procedure. All participants took part in an initial screening and practice session. Exclusion criteria included various medical conditions, such as chronic respiratory diseases and current allergic rhinitis, and taking medications that were psychoactive, pain-relieving or liable to induce drowsiness. Performance and task engagement were assessed during laboratory visits on two subsequent days. On day 1, baseline performance was assessed in a healthy state. The next session took place during the winter cold season, several months later. On day 2, about half the participants (*N* = 96) followed the same protocol while suffering from a cold. The remaining participants (*N* = 108) were retested as healthy controls. At each visit, participants were excluded if they were suffering from allergic rhinitis, if they reported using caffeine and nicotine on the day of testing, or if they had used alcohol and/or medications for cold symptoms during the previous 24 hours. Participants completed a symptom checklist, at each visit, on which they rated severity of each of five cold symptoms, such as having a runny nose, on a five-point Likert scale. Healthy participants were required to have a total symptom score of two or less, whereas infected participants were required to have a symptom score of five or more.

A battery of four tasks were performed, in a fixed order (see Matthews et al., 2001, for descriptions). All tasks involved the presentation of visual stimuli on a computer monitor, to which keypress responses were made. The first task was the variable foreperiod SRT task, followed by focused and selective attention tasks (Hall & Smith, 1996), and, finally, the Temple et al. (2000) vigilance task. The DSSQ was administered twice, before and after the entire battery of tasks. The post-task administration required participants to rate their feelings during the vigilance task. The two tasks of interest for modeling were:

Variable foreperiod simple reaction time (SRT). Each trial began with the presentation of a box stimulus. After a variable foreperiod of 1-10 s, a square appeared within the box, and the participant was required to make a keypress response as quickly as possible. Task duration was five minutes.

Vigilance. A mask stimulus comprising an array of unfilled circles that covered the entire screen was present throughout the task. A series of single, grey, letter-like stimuli was presented for 40 ms each, at a rate of 57.5/min, overlaid on the mask stimulus. The target stimulus occurred with a probability of p = .20. Participants were required to press a key in response to the target O, ignoring two nontarget stimuli: a D and a backwards D. Responses were logged for an interval of 920 ms following offset of the letter-like stimulus. This task generates rapid temporal decrement in detections when the contrast ratio between the letter-like stimuli and the white background is relatively low (Temple et al., 2000). Task duration was 12 minutes.

Results

Initial analyses. Similar to Study 1, we analyzed effects of independent factors on mean levels of task engagement and vigilance, and computed bivariate associations between these two variables. Additionally, we checked for effects of cold infection and of sample (Cincinnati or Cardiff) on the outcome measures. One participant failed to complete both instances of the vigilance task.

Effects on task engagement were analyzed using a 2 × 2 × 2 (day: 1 vs. 2 × prepost: pre-task vs. post-task × cold group: healthy on day 2 vs. infected on day 2) mixed-model ANOVA. There were repeated measures on the first two factors; cold group was a between-subjects factor. There were significant main effects of day, $F(1,203) = 120.27$, $p<.01$, $\eta^2_p = .372$, prepost, $F(1,203) = 24.60$, $p<.01$, $\eta^2_p = .108$, and cold, $F(1,203) = 7.78$, $p<.01$, $\eta^2_p = .037$. There were also three significant interactions: day × cold group, $F(1,203) = 84.27$, $p<.01$, $\eta^2_p = .293$, day × prepost, $F(1,203) = 14.73$, $p<.01$, $\eta^2_p = .068$, and day × prepost × cold group, $F(1,203) = 4.45$, $p<.05$, $\eta^2_p = .021$. Figure 4 shows these effects. On day 1, both groups showed a substantial decline in task engagement from pre- to post-task. (An additional analysis of the day 1 data showed no effects of cold group: all participants were tested when healthy). On day 2, the healthy group again showed loss of engagement post-task. However, the cold-infected group showed strongly depressed levels of engagement pre-task, with no further loss of engagement post-task, perhaps reflecting a floor effect. The Cincinnati sample tended to be higher in task engagement than the Cardiff sample, especially on day 1. In pre-task data *d*s for the sample difference were 1.00 (day 1) and 0.65 (day 2). Further analysis of the effect of sample was beyond the present scope.

Figure 4 about here

Effects on hit rate (% targets detected) were analyzed using a 2 × 6 × 2 (day: 1 vs. 2 × prepost: period: six 2-min periods × cold group: healthy on day 2 vs. infected on day 2) mixed-model ANOVA. Box's correction to degrees of freedom was applied where appropriate because of violations of the sphericity assumption. There were significant main effects of day, $F(1,202) = 11.19$, $p<.01$, $\eta^2_p = .052$, period, $F(3.617,730.730) = 47.27$, $p<.01$, $\eta^2_p = .190$, and cold group, $F(1,202) = 5.80$, $p<.05$, $\eta^2_p = .028$. There was also one significant interaction: day × cold group, $F(1,202) = 7.61$, $p<.01$, $\eta^2_p = .036$. Figure 5 shows cell means. Both groups showed similar temporal decrements in hit rate on day 1. However, the cold-infected group showed lower hit rates throughout the vigil on day 2. The magnitude of decrement was not affected either by repeated testing or by cold infection, as shown by the lack of interaction between task period and other factors. The Cardiff sample tended to show higher hit rates than the Cincinnati sample. On day 1, the two groups differed significantly in average hit rate, $t(203)=2.39$, $p<.05$, $d=0.38$) but on day 2, there was only a trend in this direction ($.05<p<.10$). Again, we did not analyze sample effects further.

Figure 5 about here

With sample controlled, partial correlations between pre- and post-task engagement and average hit rate were .20 and .19, respectively, on day 1 (both significant at $p<.01$). With both sample and cold infection controlled, the pre- and post-task partial correlations on day 2 were .20 and .31 (both significant at p<.01).

Finally, we checked for effects of study variables on variable foreperiod SRT, using a 2 × 2 (day: 1 vs. 2 × cold group: healthy on day 2 vs. infected on day 2) mixed-model ANOVA. There were significant main effects of day, $F(1,203) = 63.68$, $p<.01$, $\eta^2_p = .239$, and cold group, $F(1,203) = 11.45$, $p<.05$, $\eta^2_p = .045$, and the interaction was also significant, $F(1,203) = 25.85$, $p<.01$, $\eta^2_p = .113$. Figure 6 shows that the cold group on day 2 had slower RTs than the other groups.

Figure 6 about here

Multivariate modeling. Figure 7 shows the conceptual models of interest. Similar to Study 1, the latent factors were defined by observed variables as follows:

- *Task engagement:* post-task energetic arousal, task motivation and concentration
- *Vigilance*: hit rate for each task period (i.e., six measures)

Testing site and SRT were modeled as single-indicator variables. All models assumed that (1) task engagement has a direct influence on vigilance, and (2) engagement and vigilance on day 1 influence their counterparts on day 2 (i.e., some test-retest stability). (Models contrary to these assumptions were very poorly-fitting). In addition, SRT is seen as a facet of vigilance. The model made up of the solid paths is a full mediation model; effects of cold infection on both vigilance and SRT are entirely transmitted by changes in task engagement. The additional, broken paths reflect partial mediation models: Path A reflects an additional, direct effect of colds on vigilance, and Path B reflects a direct effect of colds on SRT. Modeling focused on whether adding these paths to the full mediation model improved fit. Some further modifications to the model were found necessary to attain adequate fits. Site was included as an additional, independent variable that influenced the latent factors, to accommodate site effects on task engagement and vigilance. The error terms of the repeated energetic arousal, motivation, concentration and SRT variables were allowed to correlate across days, i.e., these variables have reliable unique variance that is stable over time and is not captured by the latent factor. Because of violation of the multivariate kurtosis assumption, we again report robust fit statistics as well as overall χ^2.

Figure 7 about here

Model 1 was the full mediation model, which fitted the data moderately well, although CFI fell short of the .950 criterion. Model 2 added path A (partial mediation of the cold effect on vigilance), Model 3 added path B only (partial mediation of the cold effect on SRT), and Model 4 added both paths. Model 2 had minimal effect on fit, $\Delta\chi^2$ (1) = 1.78, suggesting that the cold effect on vigilance was fully mediated by engagement. However, Model 3 improved fit modestly, and the change in fit was significant, $\Delta\chi^2$ (1) = 17.41, $p<.01$, implying partial mediation of the effect on SRT. Model 4 did not improve fit significantly relative to Model 3, $\Delta\chi^2$ (1) = 1.17, again suggesting full mediation of the effect on vigilance. Fit statistics are summarized in Table 2.

Table 2 about here

Model 3 is thus preferred on grounds of fit and parsimony. That is, optimizing fit requires Path B but not Path A in Figure 7. The model is illustrated in Figure 8. For clarity, we have omitted the measured DSSQ and hit rate variables that define the latent factors; path coefficients were similar to those found in Study 1. Coefficients for the influence of the task engagement factor on energetic arousal, concentration and motivation ranged from .66 - .83 on day 1 and .63 - .79 on day 2. Coefficients for the paths from the vigilance factor to the six hit rate variables .ranged from 65 - .87 on day 1 and .74 - .86 on day 2. The Figure shows the influence of site; participants at the Cincinnati site were higher in engagement but lower in vigilance on day 1. These relationships were considerably smaller on day 2, and the site – engagement path became non-significant. All other paths were significant at $p<.05$. The Figure shows that engagement exerted a similar influence on vigilance on both days. Cold infection had indirect effects mediated by depressed task engagement on both vigilance and SRT, but there was also a significant direct path from cold to SRT.

Figure 8 about here

Discussion

As in Study 1, SEMs included a direct path from task engagement to vigilance. The Temple et al. (2000) task may draw on the same resource as the Study 1 line length discrimination task: both tasks are perceptually demanding. Study 2 further showed that the engagement – vigilance path was similar in strength across the two days of testing, even though mean levels of engagement tended to be lower on day 2. This finding is consistent with the suggestion that the performance-resource function (PRF: Norman & Bobrow, 1975) for vigilance may be approximately linear, provided that performance is resource-limited (Matthews, Holley & Davies, 1990). Each unit change in task engagement leads to a c. 0.3 SD change in vigilance. Helton et al. (2008) and Matthews et al. (2010a, 2014) obtained similar effect sizes.

Cold infection significantly depressed both vigilance and task engagement. Potentially, the change in subjective state could be incidental to performance change. However, modeling suggested that the effect of cold infection on vigilance was fully mediated by loss of task engagement, implying that infection leads to a depletion of resources that can be indexed by subjective state change. There are several possible neural mechanisms for cold effects (Eccles, 2009; Smith, 2013), including immunological changes (central cytokine production), effects on the trigeminal nerve, and changes in neurotransmitter function, as well as indirect effects of sleep loss. Eccles (2009) further notes that cytokines may alter dopamine and serotonin metabolism in the basal ganglia. Task engagement has been linked to dopaminergic afferents to frontal cortex (Matthews et al., 2010b), and so the potential role of dopamine may be especially relevant. However, it remains to be determined which specific neural mechanisms might influence both subjective task engagement and resource availability.

Modeling also showed that variable foreperiod SRT could be included as a marker for the vigilance factor. That is, the resource that influences accuracy on standard vigilance tasks may also affect speed of response on the SRT task. However, the data also suggest that the SRT task differs from standard vigilance in some respects. The measured variable had only a moderate link to the latent factor, leaving substantial variance unexplained. Good model fit required a direct path from cold infection to SRT that was not mediated by task engagement. The task may be sensitive to a psychomotor slowing effect of cold infection attributable to changes in the turnover of central noradrenaline (Smith & Nutt, 1996), which does not have a direct counterpart in subjective experience. Thus, use of the DSSQ as potential diagnostic instrument in human factors settings should be tempered by an understanding of the cognitive and motor aspects of the operational task concerned. Subjective state assessment may be most useful for tasks primarily dependent on sustained attention.

CONCLUSIONS

In the introduction, we identified four aspects of vigilance research to which Raja Parasuraman made major and lasting contributions. We conclude by evaluating the contribution of the current studies to each of these issues, and priorities for further research.

- *Simultaneous vs. successive task types*. Study 1 confirmed Parasuraman et al.'s (1987) differentiation of the two task types on psychometric grounds. However, it also showed that STM demands are only one of several factors controlling vigilance decrement; demanding, high event rate simultaneous tasks may also show substantial temporal decline in detections. A limitation of the study is that it utilized only two, visual vigilance tasks, requiring a sensory discrimination of line length. Study 2 suggested that the variable foreperiod SRT task, widely used as a proxy for vigilance in sleep deprivation research, is imperfectly aligned with the latent construct defined by these standard vigilance tasks. Thus, further work is needed to explore the dimensional structure of the wider domain of sustained attention tasks and to integrate it into existing models of cognitive ability (e.g., Schweizer, 2010). It is also challenging to discriminate general resources for vigilance, whether unitary or multiple, from specific processes such as retention in STM, although this problem is not unique to vigilance (Matthews, Davies, Westerman & Stammers, 2000). Indeed, current work on visual attention continues to be divided between approaches favoring unitary resource theory (Pastukhov, Fischer, & Braun. 2009), and those that differentiate multiple types of attention (Carrasco, 2011; Chun, Golomb, & Turk-Browne, 2011). Further research needs to be directed towards differentiating domain-specific and domain-general mechanisms in vigilance (Helton & Russell, 2013).
- *The role of arousal.* Study 2 confirmed Davies and Parasuraman's (1982) conclusion that de-arousing stressors tend to impair vigilance, although in this case cold infection tended to impair overall level of vigilance rather than accentuate vigilance decrement. Davies and Parasuraman (1982) emphasized the variability of effects of different stressors, pointing to the limitations of a simple arousal theory explanation. Similarly, Matthews and Davies (1998) noted that energetic arousal appears to be more closely linked to vigilance than is tense arousal; use of the task engagement factor to capture subjective energy may be one of the more effective ways of

exploring arousal processes. Parasuraman's (e.g., 2003) later work on neuroergonomics advocated for a more differentiated view of neural bases of attention, an approach that has been productive in understanding the impact of the common cold (Eccles, 2009; Smith, 2013). Current vigilance research suggests that hemodynamic indices of frontal brain metabolism such as CBFV (Warm et al., 2012) and EEG measures (Kamzanova, Kustubayeva, & Matthews, 2014) may be more diagnostic of vigilance than traditional autononic arousal measures.

However, both self-report and psychophysiological measures have significant limitations for diagnostic purposes. Self-reports provide only a limited window into neural substrates of vigilance, although they capture self-regulative processes such as coping that are important for compensating for stress and fatigue (Matthews et al., 2014). Psychophysiological measures of different response systems are typically poorly intercorrelated, and so fail to meet psychometric criteria for valid measurement of broad-based constructs such as stress (Fahrenberg et al., 1983) and workload (Matthews, Reinerman-Jones, Barber & Abich, 2015). Future research may succeed in identifying psychophysiological metrics for the specific brain structures and processes that contribute to vigilance (e.g., Langner & Eickhoff, 2013).

- *Individual differences in vigilance.* Research on cognitive ability (Matthews et al., 2014) and task engagement (Matthews et al., 2010b) has progressed beyond Davies and Parasuraman's (1982) pessimistic evaluation of individual differences studies. Both of the present studies showed that multivariate modeling of individual differences requires paths from engagement to vigilance, consistent with previous modeling studies (Helton et al., 2008; Matthews et al., 2010a, 2014). The data are consistent with engagement indexing a general attentional resource important for a range of different vigilance tasks (Matthews et al., 2010b), although the respective roles of multiple resources and specific cognitive processes remain to be clarified. Limitations here are primarily those of interpretation: what causal processes are actually indexed by a verbal report of a conscious feeling state of engagement? Possible answers include brain systems, such as those supporting executive control, 'virtual' processing constructs such as resources, and task strategies such as problem-focused coping and investment of effort (Matthews et al., 2010b). For example, impacts of resource deficiency associated with low task engagement might be amplified by reduction of task-directed effort. While data are consistent with Parasuraman et al.'s (1987) theory, 'resources' remain elusive psychometrically (Matthews et al., 2014). We also focused on overall level of vigilance as a resource indicator, but future research could model individual differences in the decrement function in more detail.

Finally, over his luminary career Raja Parasuraman turned increasingly to applied human factors issues, although always from a solid theoretical foundation (e.g., Parasuraman, Sheridan, & Wickens (2008). He realized that operational vigilance problems would occur in the context of monitoring automated systems (Parasuraman, Mouloua & Molloy, 1996). Individual differences research can then contribute to selection and diagnostic monitoring of operators (e.g., Singh, Molloy & Parasuraman, 1993). Assessment of subjective state may have a part in such efforts, in conjunction with objective measurement. Matthews et al. (2010a) showed that assessment of engagement and CBFV responses to short but cognitively challenging tasks afforded prediction of the person's performance on subsequent, longer sensory and cognitive vigilance tasks. Recent studies have shown that the predictive validity of the DSSQ extends to signal detection elements of simulated operation of partly-automated unmanned ground and aerial vehicles (Abich, Matthews & Reinerman-Jones, 2015). Raja Parasuraman's pioneering work on vigilance, neuroergonomics, and automated systems provides a basis for understanding individual differences in sustained attention in the rapidly-developing technologies of the 21st century.

KEY POINTS

- Raja Parasuraman's work on vigilance identified several critical theoretical and applied issues that may be framed within attentional resource theory
- Subjective task engagement may be a marker for attentional resource availability, and so assessment of engagement may contribute to investigating various vigilance issues
- Structural equation modeling differentiated simultaneous and successive vigilance factors and showed that task engagement directly impacts simultaneous vigilance (Study 1)
- Modeling also showed that task engagement fully mediates adverse effects of cold infection on vigilance, but not on variable foreperiod reaction time (Study 2)
- Results contribute to elaborating resource models of vigilance, and to diagnostic monitoring of operators in applied settings

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Tables

Table 1. Summary of goodness of fit statistics for four models (Study 1).

Model	df	χ^2	SBS χ^2	CFI	RMSEA	90% CI for RMSEA
1	43	643.27**	530.62**	.669	.230	.212-.214
2	41	135.30**	112.30**	.952	.090	.070-.110
3	42	137.24**	114.82**	.951	.090	.070-.109
4	42	150.27**	125.94**	.943	.096	.076-.116

Note. ** $p<.01$. SBS = Satorra-Bentler scaled, CFI = Comparative Fit Index, RMSEA = Root Mean-Square Error of Approximation (RMSEA), CI = Confidence Interval.

Table 2. Summary of goodness of fit statistics for four models (Study 2).

Model	df	χ^2	SBS χ^2	CFI	RMSEA	90% CI for RMSEA
1	198	369.73**	296.07**	.939	.049	.037-.061
2	197	367.95**	294.34**	.939	.049	.037-.061
3	197	352.32**	281.17**	.948	.046	.033-.057
4	196	351.15**	280.06**	.948	.046	.033-.058

Note. ** p<.01. SBS = Satorra-Bentler scaled, CFI = Comparative Fit Index, RMSEA = Root Mean-Square Error of Approximation (RMSEA), CI = Confidence Interval.

Figure Captions

Figure 1. Stimuli for Study 1 task.

Figure 2. Effects of 4-min task period on hit rate for simultaneous (SIM) and successive (SUC) vigilance tasks (Study 1). Error bars in this and subsequent figures are standard errors.

Figure 3. Standardized path coefficients for Model 3 (Study 1). Task engagement is defined by post-task DSSQ measures. Errors and disturbances are omitted.

Figure 4. Effects of day, pre- vs. post-task administration and cold group on task engagement (Study 2)

Figure 5. Effects of day, 2-min task period and cold group on hit rate (Study 2).

Figure 6. Effects of day and cold group on variable foreperiod SRT (Study 2).

Figure 7. Mediating and direct paths tested in SEMs (Study 2).

Figure 8. Standardized path coefficients for Model 3 (Study 2). Task engagement is defined by post-task DSSQ measures. Errors, disturbances and inter-error correlations are omitted. DSSQ and vigilance measured variables defining task engagement and vigilance factors are also omitted. Broken path is non-significant.

Figure 1

Non-target
Stimulus

Target Stimulus
(Simultaneous)

Target Stimulus
(Successive)

Figure 2

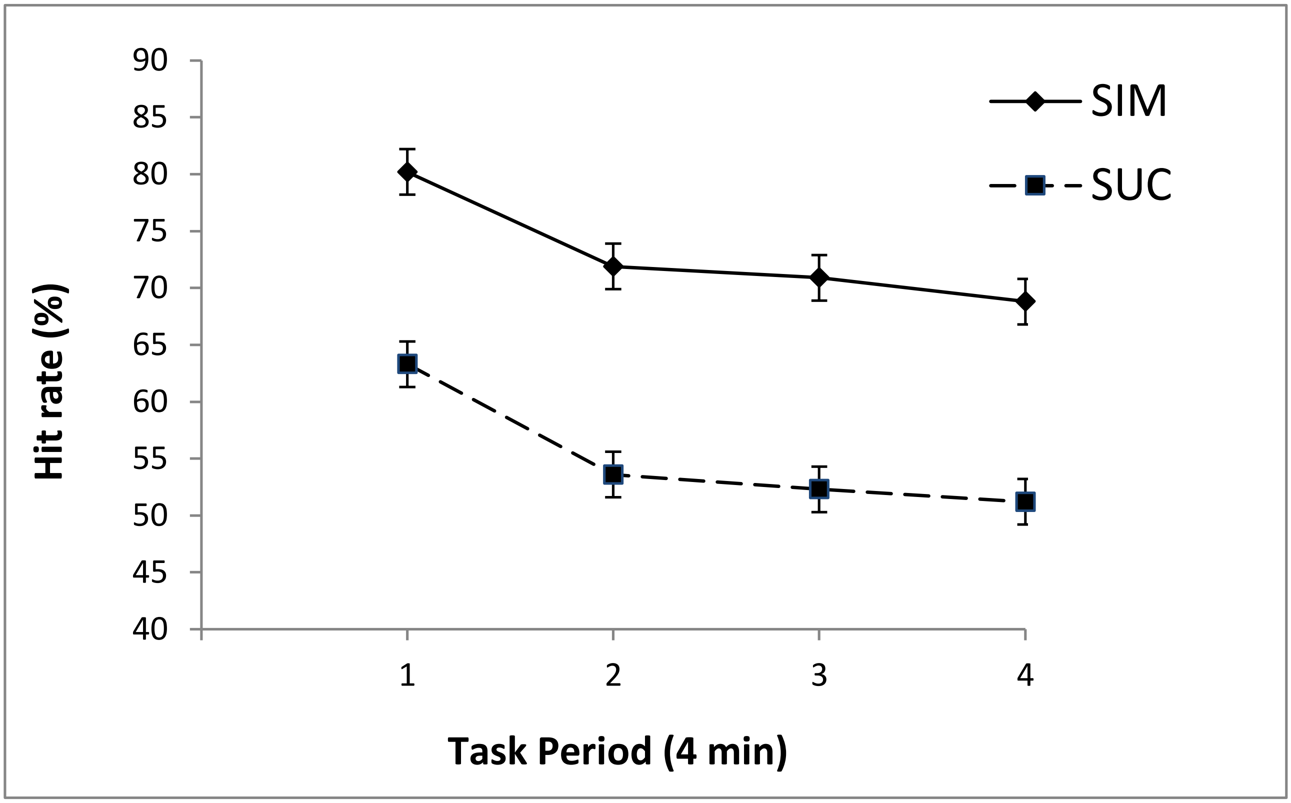

90
85
80
75
70
65
60
55
50
45
40
Hit rate (%)
1
2
3
4
Task Period (4 min)
SIM
SUC

Figure 3

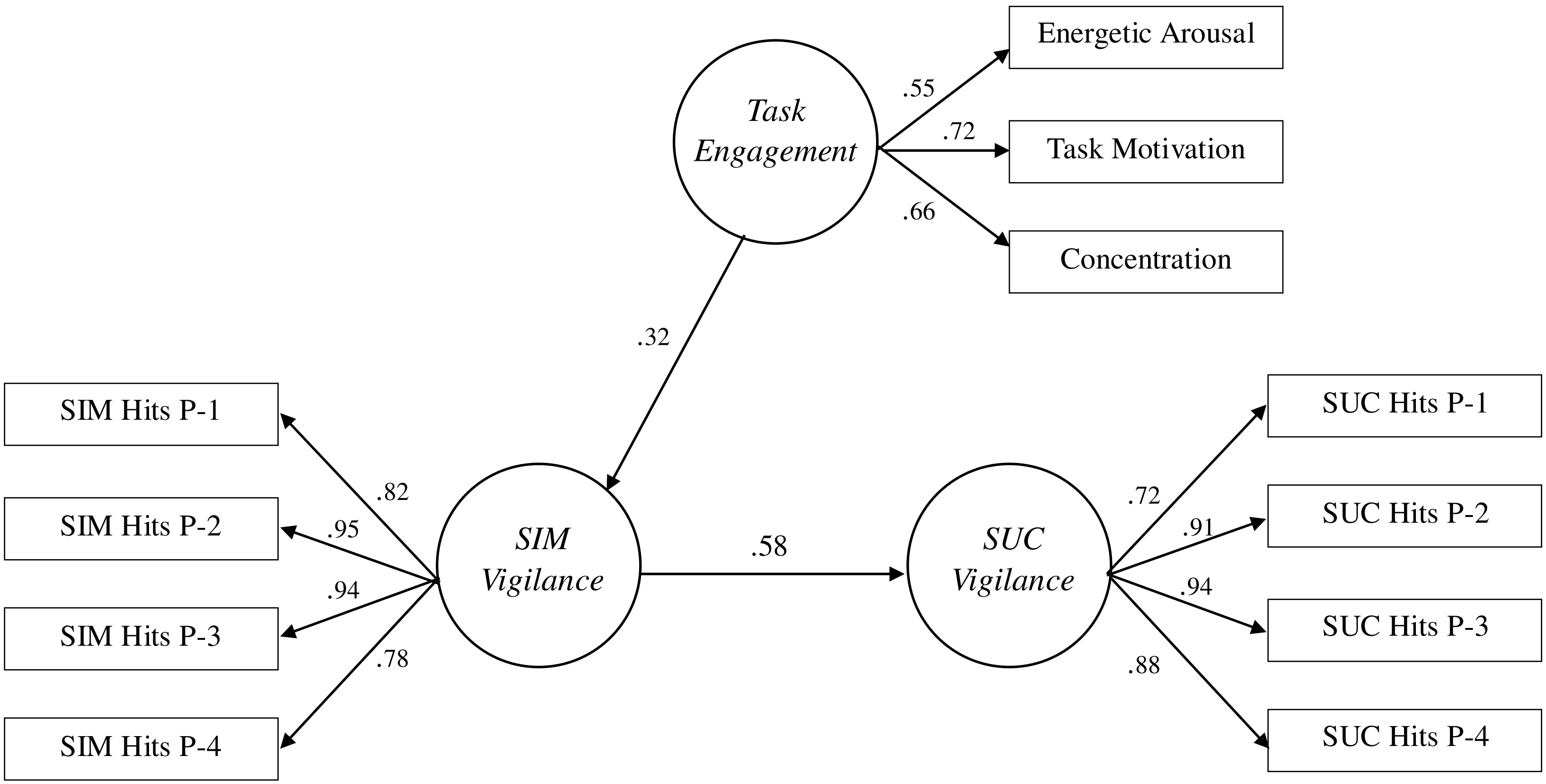

Task
Engagement
Energetic Arousal
Task Motivation
Concentration
.55
.72
.66
.32
SIM Hits P-1
SIM Hits P-2
SIM Hits P-3
SIM Hits P-4
.82
.95
.94
.78
SIM
Vigilance
.58
SUC
Vigilance
SUC Hits P-1
SUC Hits P-2
SUC Hits P-3
SUC Hits P-4
.72
.91
.94
.88

Figure 4

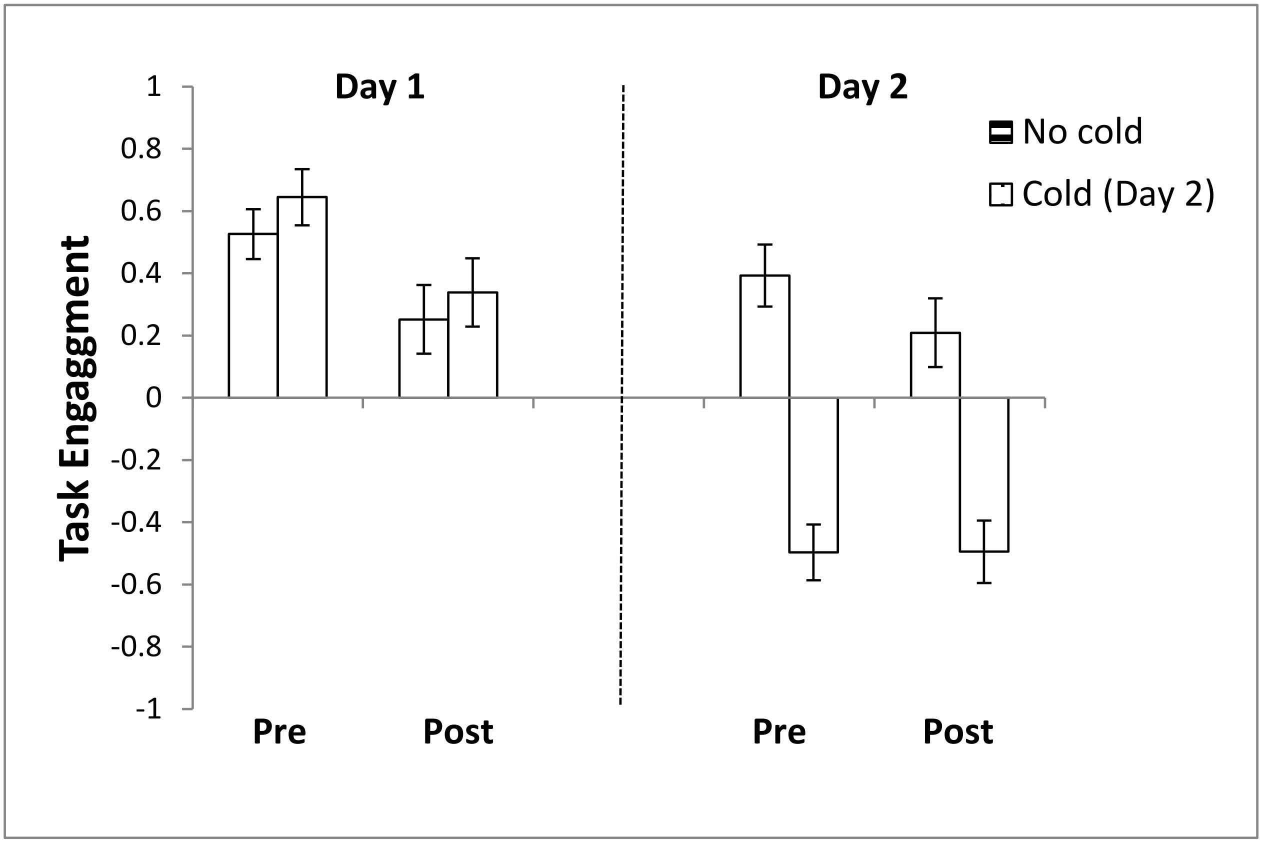

Day 1
Day 2
No cold
Cold (Day 2)
Task Engaggment
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Pre
Post
Pre
Post

Figure 5

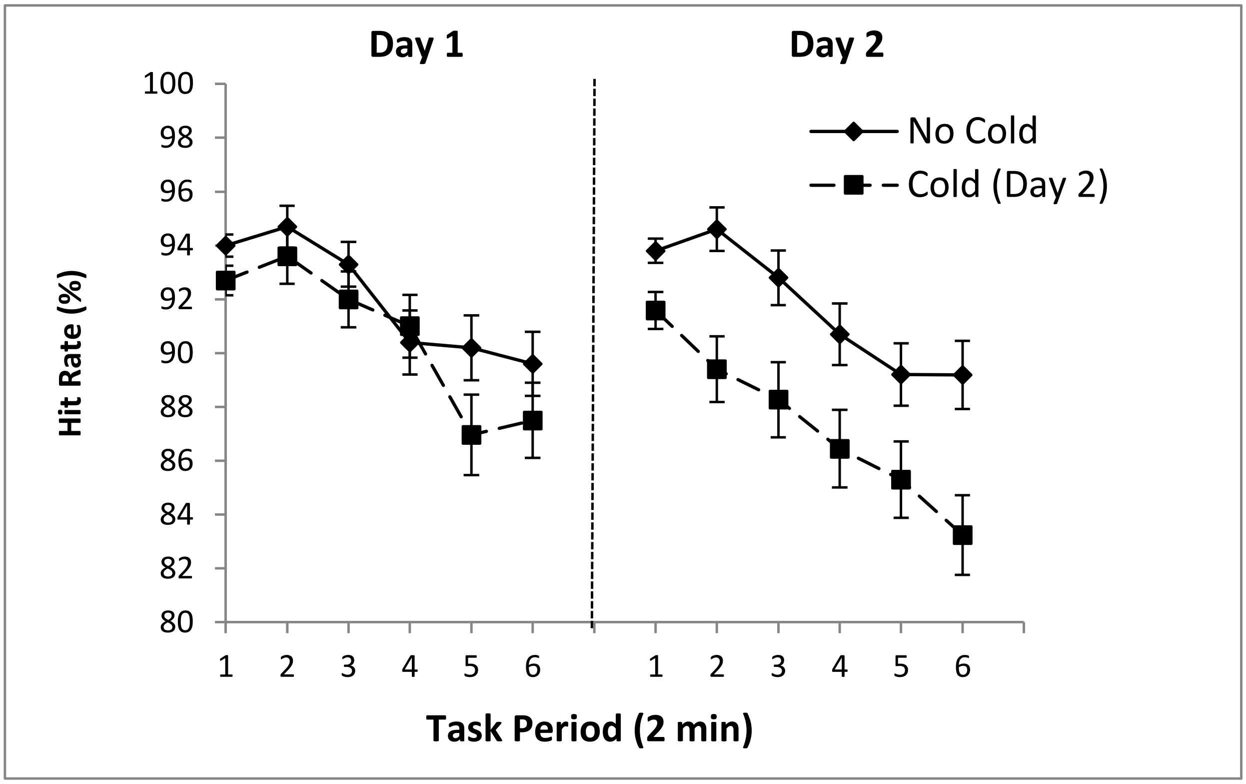

Day 1
Day 2
No Cold
Cold (Day 2)
Hit Rate (%)
100
98
96
94
92
90
88
86
84
82
80
1
2
3
4
5
6
1
2
3
4
5
6
Task Period (2 min)

Figure 6

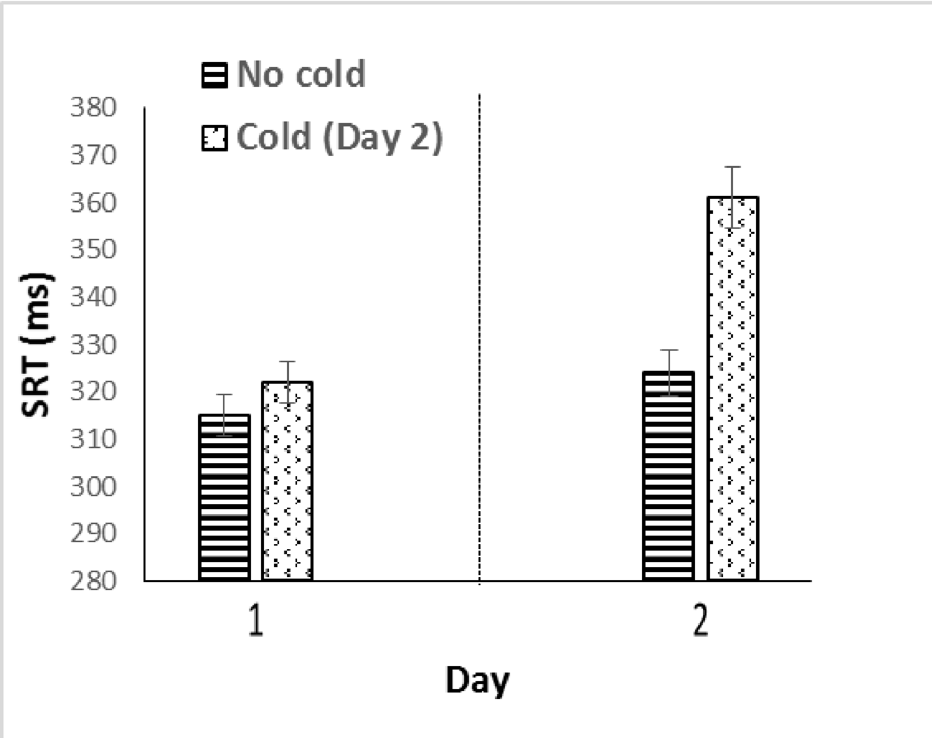

No cold
Cold (Day 2)
380
370
360
350
340
330
320
310
300
290
280
SRT (ms)
1
2
Day

Figure 7

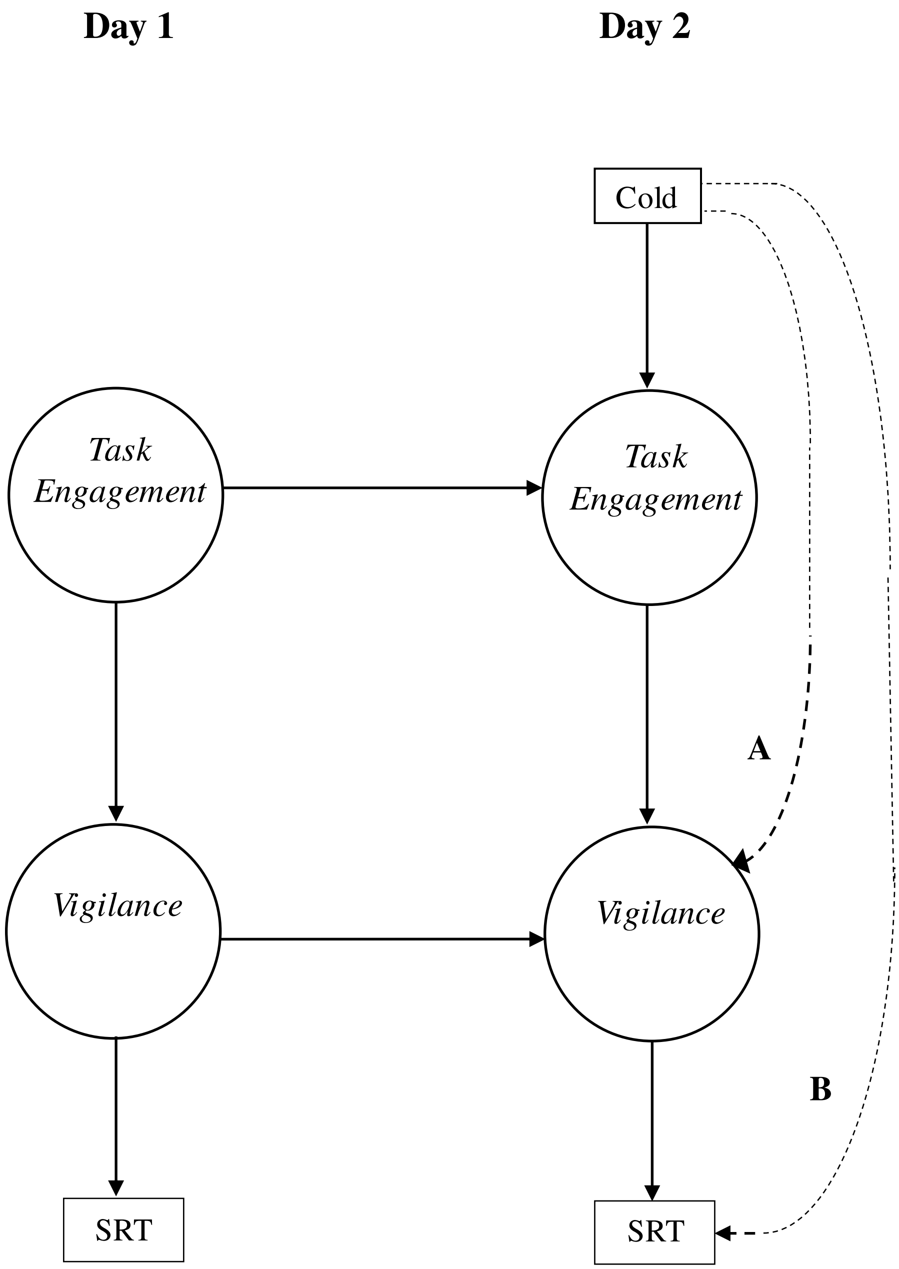
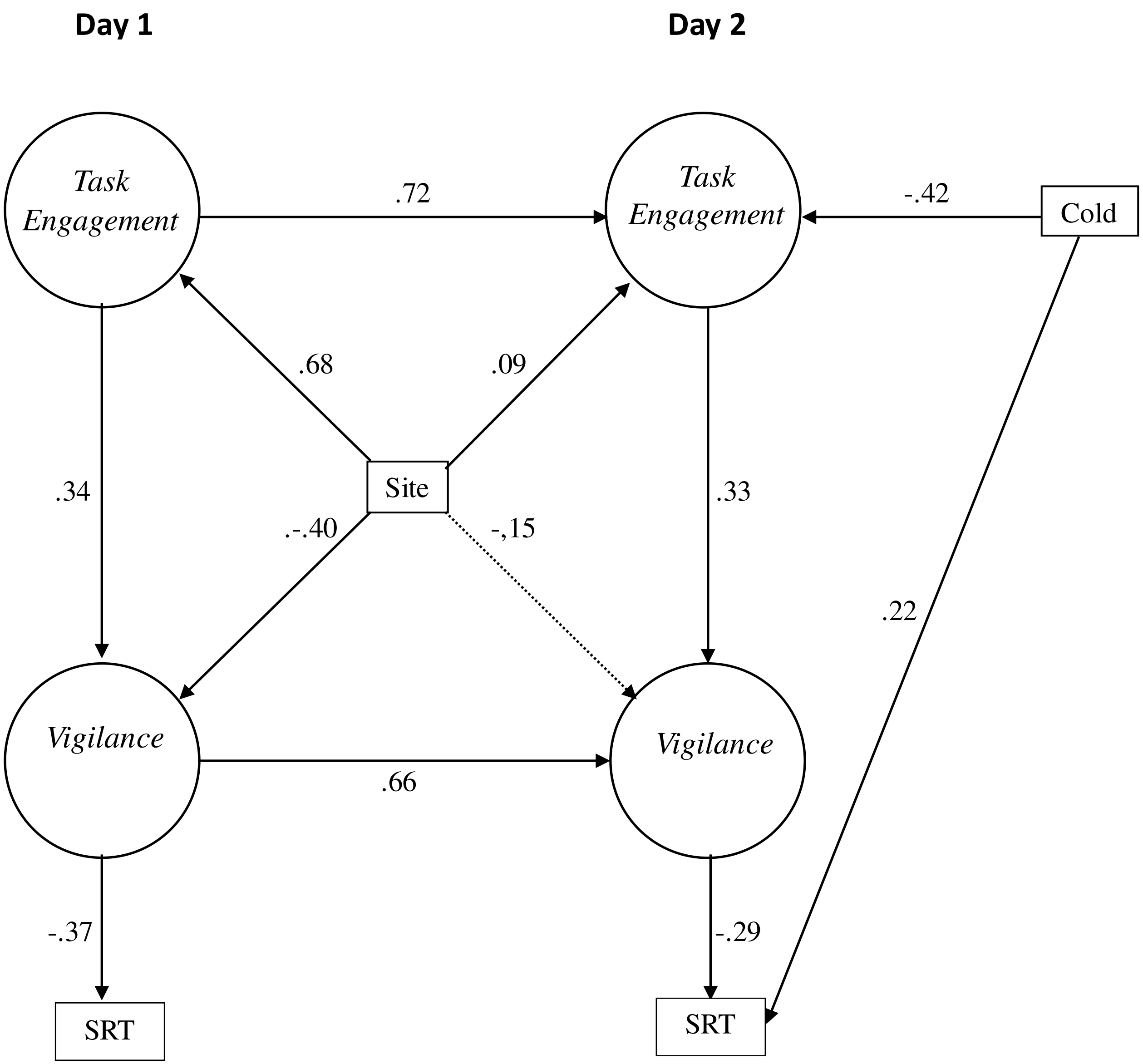

Day 1
Day 2
Cold
Task Engagement
Task Engagement
A
Vigilance
Vigilance
B
SRT
SRT

Figure 8


Day 1
Day 2
Task Engagement
.72
Task Engagement
-.42
Cold
.68
.09
.34
Site
.33
.-.40
-,15
.22
Vigilance
Vigilance
.66
-.37
-.29
SRT
SRT